

Influence of Gamma-Ray Emission on the Isotopic Composition of Clouds in the Interstellar Medium

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Abstract

We investigate one mechanism of the change in the isotopic composition of cosmologically distant clouds of interstellar gas whose matter was subjected only slightly to star formation processes. According to the standard cosmological model, the isotopic composition of the gas in such clouds was formed at the epoch of Big Bang nucleosynthesis and is determined only by the baryon density in the Universe. The dispersion in the available cloud composition observations exceeds the errors of individual measurements. This may indicate that there are mechanisms of the change in the composition of matter in the Universe after the completion of Big Bang nucleosynthesis. We have calculated the destruction and production rates of light isotopes (D, ³He, ⁴He) under the influence of photonuclear reactions triggered by the gamma-ray emission from active galactic nuclei (AGNs). We investigate the destruction and production of light elements depending on the spectral characteristics of the gamma-ray emission. We show that in comparison with previous works, taking into account the influence of spectral hardness on the photonuclear reaction rates can increase the characteristic radii of influence of the gamma-ray emission from AGNs by a factor of 2-8. The high gamma-ray luminosities of AGNs observed in recent years increase the previous estimates of the characteristic radii by two orders of magnitude. This may suggest that the influence of the emission from AGNs on the change in the composition of the medium in the immediate neighborhood (the host galaxy) has been underestimated.

Key words. cosmology, primordial composition of matter, gamma-ray emission

1. Introduction

The relative abundance of the light elements (H, D, ³He, ⁴He, ⁶Li, ⁷Li) produced at the epoch of Big Bang nucleosynthesis is one of the criteria for testing the standard cosmological model. According to this model, Big Bang nucleosynthesis occurred in the early Universe: at times from several minutes, when the Universe was extremely hot ($T > 10^9$ K), to half an hour, when the temperature and density of the medium dropped to values at which the nuclear reactions no longer proceeded. Subsequently, the composition of the interstellar and intergalactic medium changed mainly under the influence of astration and radioactive decay. Therefore, by studying the isotopic composition of distant clouds of interstellar gas ($z \sim 2 \div 3$), where the star formation processes had not yet strongly affected the relative elemental abundances, their abundances at the completion time of Big Bang nucleosynthesis can be determined.

One of the most important aspects of such an analysis is the abundance of deuterium. In comparison with other elements produced at the epoch of Big Bang nucleosynthesis, deuterium has the simplest nuclear structure and is most sensitive to a change in the baryon density Ω_b – one of the key parameters of the standard cosmological model. The D/H ratio in the interstellar

medium of galaxies can be calculated from the absorption by neutral gas of light emitted by distant quasars (QSO) by comparing the intensities of hydrogen absorption lines with those of deuterium ones. When the primordial D/H ratio is estimated, deuterium is commonly assumed to be only destroyed in the course of stellar evolution. Therefore, any D/H estimate is considered only as a lower limit for the primordial D/H ratio.

Some of the first deuterium abundance measurements in clouds of interstellar gas at high redshifts gave large D/H ratios, $\sim 10^{-4}$ (Webb et al. 1997; Rugers and Hogan 1996), which was inconsistent with the predictions of the standard model. An overview of the possible mechanisms of the change in the abundances of light elements in clouds of interstellar gas relative to their primordial values was provided by Gnedin and Ostriker (1992). However, the new deuterium abundance observations (Burles and Tytler 1998) disproving the previous ones were in agreement with the theory, and the question about the change in abundance was essentially lifted. The currently available light-element abundance data taken from Steigman (2007) are presented in Table 1. Eleven absorption systems of atomic deuterium and hydrogen have been detected in the last ten years, and the D/H ratio has been measured in them with a high accuracy. The derived values are consistent, in order of magnitude, with the conclusions of the standard model, but there are some problems. At present, only seven systems in which the deuterium

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abundance can be determined with good confidence from an analysis of absorption lines (Pettini et al. 2008, $D/H = 2.82 \pm 0.20 \times 10^{-5}$) are used to estimate the D/H ratio. However, even for this sample the 1σ scatter of D/H values was about 20%, which is considerably higher than the observational errors of individual measurements.

It is believed that the scatter of deuterium abundances in such clouds can be provided by both star formation processes and deuterium depletion onto dust grains (Linsky et al. 2006). The interstellar gas that was subjected only slightly to chemical enrichment, as is suggested by the low relative abundance of heavy elements, $O/H < 1/10$ of the value measured in the Solar system, was studied in these seven systems. In the model of galactic chemical evolution, the decrease in the D/H ratio for such clouds is negligible, which was theoretically shown by Akerman et al. (2005), Prantzos and Ishimaru (2001), and Romano et al. (2006). Therefore, the large dispersion in the experimental data is most likely explained by an underestimation of the statistical and systematic errors (Steigman 2007; Pettini et al. 2008). Apart from the standard theory of Big Bang nucleosynthesis, the dispersion in the light-element abundance observations is associated with the evaporation of primordial black holes or the decay of long-lived X-particles. The high-energy hadrons and photons being produced during the decay of X-particles destroy the light elements synthesized in Big Bang nucleosynthesis. Effective ${}^4\text{He}$ destruction and D, T, ${}^3\text{He}$ production can occur as a consequence of this process. These processes were investigated by Zeldovich et al. (1977), Kawasaki et al. (2005), and Carr et al. (2010). Stringent constraints were placed on the primordial abundance of the long-lived exotic X-particles.

In this paper, we investigate one mechanism of the change in the relative composition of the medium that was previously considered by Boyd et al. (1989) and Gnedin and Ostriker (1992). Hard X-ray and gamma-ray emission is present in the spectrum of active galactic nuclei (AGNs). Propagating in the Universe, the high-energy gamma emission interact with the interstellar and intergalactic matter. The photodisintegration of ${}^4\text{He}$ with the production of D can be compared with the photodisintegration of D. This can cause both a decrease and an increase in the relative abundance of deuterium in some regions of interstellar gas. The magnitude of this effect depends on the initial composition of the medium (the abundance of ${}^4\text{He}$ in a cloud is greater than that of D by three orders of magnitude), the spectral hardness of the gamma-ray emission characterized by the parameter Γ (see Eq. 3), and its flux.

Boyd et al. (1989) estimated this effect using the galactic center of NGC 4151 as an example. The authors showed that the gamma-ray source associated with the galactic center could cause ${}^4\text{He}$ photodisintegration and significant D production. However, the radius of influence of this process is very small and does not exceed 10 light-years in the case under consideration. The authors conclude that, given the rarity of gamma-ray sources in the Galaxy, the change in the isotopic composition of the Galactic medium is, in general, unlikely. Nevertheless, Casse et al. (1999) pointed out that blazars could affect the composition of the matter ac-

Table 1. Primordial isotopic composition of matter in the Universe

Element abundance relative to hydrogen ^a	Primordial value ^b
$X_D \equiv n_D/n_H$	2.68×10^{-5}
$X_3\text{He} \equiv n_{3\text{He}}/n_H$	1.06×10^{-5}
$X_4\text{He} \equiv n_{4\text{He}}/n_H$	7.90×10^{-2}
$X_{7\text{Li}} \equiv n_{7\text{Li}}/n_H$	4.30×10^{-10}

^a n – is the element number density in the medium.

^b The data were taken from Steigman (2007). The abundances were reconciled with the baryon density Ω_B obtained by analyzing the CMB anisotropy data.

creting onto a black hole. When outflowing from the blazars central region, this matter can condense into intergalactic clouds. The authors also note that the final D abundance is sensitive to the spectral index of the quasar emission. However, the authors made no quantitative estimations.

The goal of this paper is to consider the mechanism of element photodisintegration in a medium by the hard X-ray and gamma-ray emission from quasars by taking into account various spectral indices of emission and the high gamma-ray luminosities (compared to the values used by Boyd et al. 1989).

2. THE CROSS SECTIONS FOR PHOTONUCLEAR REACTIONS

One of the main points of our work is the determination of photonuclear reaction rates. To calculate the reaction rates in a medium irradiated by a gamma-ray flux with various spectral indices Γ , the dependence of the reaction cross sections on the gamma-ray energy should be known.

For deuterium (the simplest nuclear system), the dependence of the interaction cross section on the gamma-ray energy E can be calculated analytically (Bethe and Peierls 1935) and is written as:

$$\sigma(E) = \sigma_0 Q^{3/2} \frac{(E - Q)^{3/2}}{E^3} \quad (1)$$

where σ_0 is a dimensional constant, and Q is the reaction threshold. This dependence of the cross section on the gamma-ray energy describes well the experimental data on deuterium photodisintegration (see Fig. 1).

Other elements have a more complex nuclear structure, and the theoretical calculations for many of them are not in satisfactory agreement with the experimental data (Dzhibuti et al. 1965; Balestra et al. 1977). Figure 2 presents the experimental photonuclear reaction cross sections and their fits. The dependence of the reaction cross sections for other elements on the gamma-ray energy is similar to the deuterium reaction cross section: there exist a threshold energy starting from which the reaction proceeds and a power-law decrease in the cross section. Taking this into account, we chose functions of

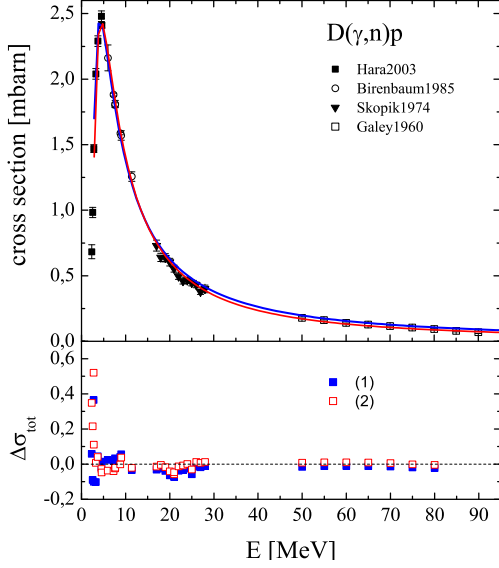


Figure 1. Cross section for the $D(\gamma, n)p$ reaction versus γ -ray energy E . The dots indicate the experimental data from Hara et al. (2003), Birenbaum et al. (1985), Skopik et al. (1974), and Galey (1960). The solid curve was computed using Eq. (1) with $\sigma_0 = 19.52$ mbarn, $\chi^2 = 286.0$. The dashed line represents fit (2) with the following parameters: $\sigma_0 = 14.3$ mbarn $\beta = 1.19$, $\gamma = 2.55$, $\chi^2 = 173.5$.

the following form for the fit:

$$\sigma(E) = \sigma_0 \frac{(\epsilon - 1)^\beta}{\epsilon^\gamma}, \quad (2)$$

where σ_0 , β and γ are the parameters of the fit, and $\epsilon \equiv E/Q$ is the dimensionless energy. The best-fit parameters are given in Table 2. For three ${}^4\text{He}$ destruction reactions, the cross section near the threshold and at high energies cannot be described by one function. Therefore, for a more accurate fit, the energy range was divided into two parts, each of which was fitted independently. For the ${}^4\text{He}(\gamma, 2p2n)$ reaction, there is a discrepancy in the absolute value of the cross section and the position of the maximum between the data from Arkatov et al. (1969, 1970), Gorbunov (1969), and Balestra et al. (1977). As was pointed out by Arkatov et al. (1970), this is because some arbitrariness is admitted when separating the individual events of the (γ, pn) and $(\gamma, 2p2n)$ reactions. In this case, the cross section was described by two functions, one of which was constructed from the data by Arkatov et al. (1970) and the other function was constructed from the data by Gorbunov (1969) and Balestra et al. (1977). However, the contribution from the ${}^4\text{He}(\gamma, 2p2n)$ reaction to the change in the abundance of the elements is so small that the difference between the two fits does not lead to a noticeable change in the final result.

Given the high gamma-ray energy, the photodisintegration reaction products can have a kinetic energy exceeding their binding energy. In this case, the thermalization of high-energy D and ${}^3\text{He}$ nuclei in the medium should be considered separately. Mostly the nuclei will collide with cold protons and will reduce its energy or

be destroyed, depending on the energy of the colliding particles and the scattering pattern (elastic, inelastic). Deuterium has a low binding energy, $Q_D = 2.23$ MeV, will be most sensitive to the thermalization process. The width of the reaction cross section maximum is $\Delta E \sim 2 \div 10$ MeV (see Fig. 2 and Table 2). The kinetic energy of the produced nuclei can be estimated as $E_k \simeq \Delta E/2$, which can exceed the deuterium binding energy Q_D . Therefore, the thermalization of D and ${}^3\text{He}$ nuclei in the medium can partially destroy the produced amount of elements.

Thus, complex statistical calculations of the thermalization of nuclei required to reliably estimate the amount of produced D and ${}^3\text{He}$ nuclei. In this paper, we consider the effect that consists in a great change in the abundance of light nuclei in the medium irradiated by emission with various values of the spectral hardness Γ . This effect turns out to be especially important in the immediate vicinity of AGNs.

3. OBSERVATIONAL DATA ON ACTIVE GALACTIC NUCLEI

Blazars and quasars (AGNs) are extremely intense sources of energy release in the Universe; they also have enormous gamma-ray luminosities. Since gamma rays with an energy above 2.23 MeV (the deuterium binding energy) are involved in the photodisintegration of elements, we are interested in the gamma-ray energy range from 1 to 1000 MeV. The upper boundary was chosen with some margin: since the quasar spectrum falls off as a power law, taking into account the energy range from 100 to 1000 MeV causes the reaction rates to increase by no more than 1%.

The spectra of such objects were investigated at the orbital observatories: AGILE (30-500 MeV; see, e.g., D'Ammando et al. 2011), COMPTEL (0.75-30 MeV; see, e.g., Schonfelder et al. 2000), EGRET (30 MeV-20 GeV; see, e.g., Hartman et al. 1999), and Fermi LAT (20 MeV-300 GeV; see, e.g., Abdo et al. 2010).

In the region of photonuclear reaction thresholds (2-30 MeV), there are data on the spectra from the survey by Schonfelder et al. (2000). As was shown in the surveys by Hartman et al. (1999) and Schonfelder et al. (2000), the quasar emission at high energies ($E_\gamma > 1$ MeV) is well fitted by a power law:

$$F_\gamma(E) = F_0 \left(\frac{E}{\epsilon_0} \right)^{-\Gamma} \quad (3)$$

where F_0 is a flux density in $\text{phot cm}^2 \text{s}^{-1} \text{MeV}^{-1}$, Γ is the spectral index, and ϵ_0 is the scale factor. Their typical values are $F_0 \sim 10^{-8} \text{ phot cm}^2 \text{s}^{-1} \text{MeV}^{-1}$, $\Gamma = 1 \div 4$, $\epsilon_0 = 1 \div 300$ MeV.

4. KINETICS OF THE ISOTOPIC COMPOSITION OF THE INTERSTELLAR MEDIUM

The kinetics of the isotopic composition of the interstellar medium as a function of the exposure time and

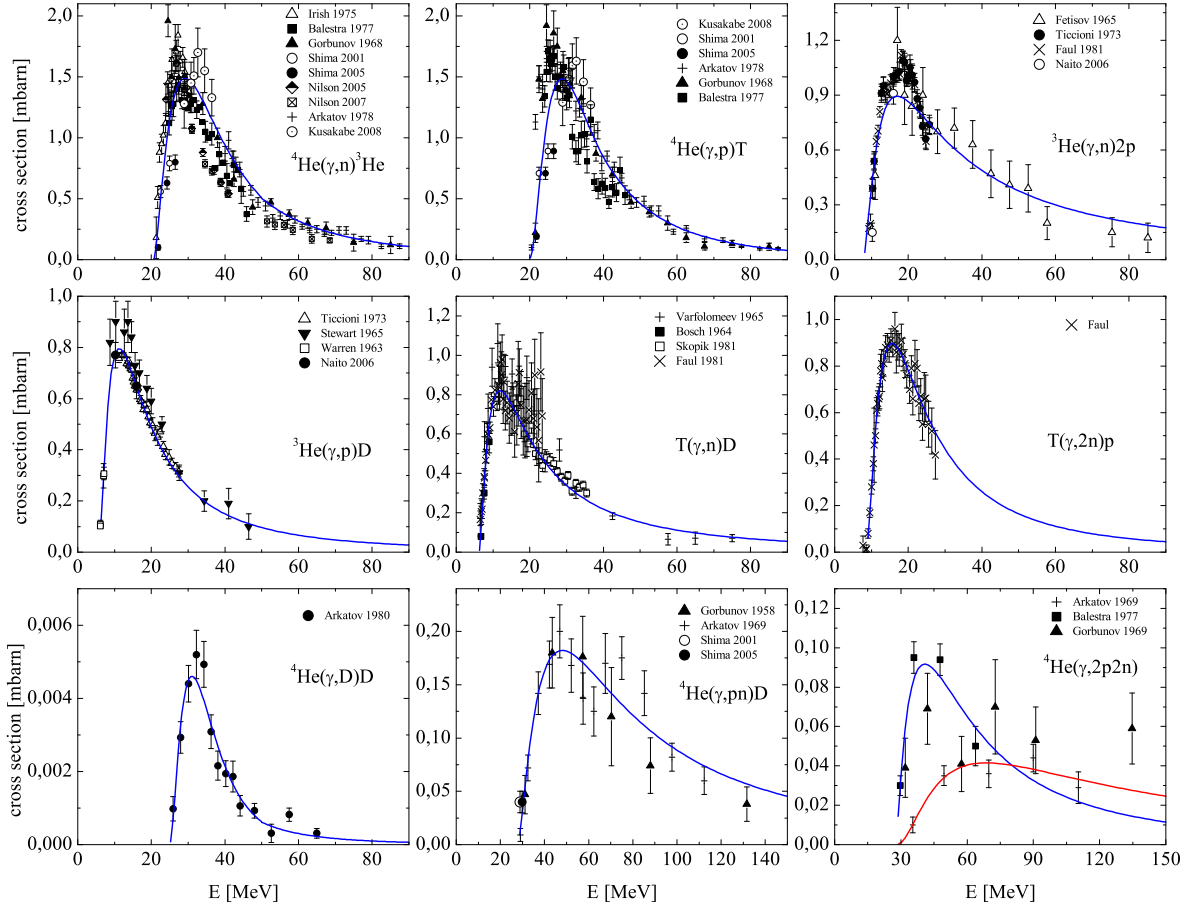


Figure 2. Photonuclear reaction cross sections versus γ -ray energy E . The solid curves represent fit (2) with σ_0, β, γ from Table 2. The dots indicate the experimental data: $T(\gamma, n)D$ Varfolomeev and Gorbunov (1965), Bosch et al. (1964), Skopik et al. (1981), Faul et al. (1981); $T(\gamma, 2n)p$ Faul et al. (1980). ${}^3\text{He}(\gamma, p)D$ Ticcioni et al. (1973), Stewart et al. (1965), Warren et al. (1963), Naito et al. (2006); ${}^3\text{He}(\gamma, n)2p$ Fetisov et al. (1965), Ticcioni et al. (1973), Faul et al. (1981), Naito et al. (2006); ${}^4\text{He}(\gamma, p)T$ Shima et al. (2001,2005), Kusakabe et al. (2009), Arkatov et al. (1978b), Gorbunov (1968), Balestra et al. (1977); ${}^4\text{He}(\gamma, n){}^3\text{He}$ Irish et al. (1975), Balestra et al. (1977), Gorbunov (1968), Shima et al. (2001,2005), Kusakabe et al. (2009), Nilson (2005,2007), Arkatov (1978a); ${}^4\text{He}(\gamma, D)D$ Arkatov et al. (1980); ${}^4\text{He}(\gamma, pn)D$ Shima et al. (2001,2005), Arkatov et al. (1969b), Gorbunov (1958); ${}^4\text{He}(\gamma, 2p2n)$ Balestra et al. (1977), Arkatov et al. (1969a), Gorbunov (1969).

spectral parameters can be obtained by solving the system of ordinary differential equations (4 - 7):

$$\frac{dX_{4\text{He}}}{dt} = -(k_{4\text{He} \rightarrow T} + k_{4\text{He} \rightarrow {}^3\text{He}} + k_{4\text{He} \rightarrow D+D} + k_{4\text{He} \rightarrow D+pn} + k_{4\text{He} \rightarrow 2p+2n})X_{4\text{He}} \quad (4)$$

$$\frac{dX_T}{dt} = -(k_{T \rightarrow {}^3\text{He}} + k_{T \rightarrow D} + k_{T \rightarrow 2n+p})X_T + k_{4\text{He} \rightarrow {}^3\text{He}}X_{4\text{He}} \quad (5)$$

$$\frac{dX_{{}^3\text{He}}}{dt} = -(k_{{}^3\text{He} \rightarrow D} + k_{{}^3\text{He} \rightarrow n+2p})X_{{}^3\text{He}} + k_{4\text{He} \rightarrow {}^3\text{He}}X_{4\text{He}} + k_{T \rightarrow {}^3\text{He}}X_T \quad (6)$$

$$\frac{dX_D}{dt} = -k_{D \rightarrow p+n}X_D + (2 \cdot k_{4\text{He} \rightarrow D+D} + k_{4\text{He} \rightarrow D+pn})X_{4\text{He}} + k_{{}^3\text{He} \rightarrow D}X_{{}^3\text{He}} + k_{T \rightarrow D}X_T, \quad (7)$$

where X denote the elemental abundances, and k are the photonuclear reaction rates. The element abundances calculated using the theory of Big Bang nucleosynthesis

with the baryon density Ω_B obtained by analyzing the cosmic microwave background (CMB) anisotropy data (see Table 1) were taken as the medium's initial composition. The influence of the elements with an atomic weight greater than that of ${}^4\text{He}$ on the change in the abundances of lighter elements may be neglected, because their relative abundance in a medium similar to the primordial one is low ($({}^7\text{Li}/\text{H}) \leq 5 \times 10^{-10}$), while the cross sections are of the same order of magnitude (see Berman et al. 1965; Varlamov et al. 1986). Using Eqs. (2) and (3), the photonuclear reaction rates can be written as:

$$k = \int_Q^\infty \sigma(E) F_\gamma(E) dE = 10^{-27} \left(\frac{\sigma_0}{1 \text{ mbarn}} \right) \times F_0 \varepsilon_0^\Gamma \left(\frac{Q}{1 \text{ MeV}} \right)^{1-\Gamma} \int_1^{1000/Q} \frac{(x-1)^\beta}{x^{\gamma+\Gamma}} dx, \quad (8)$$

Table 2. Parameters of the fit to the photonuclear cross sections ^a.

Reaction	Q, MeV	E _γ , MeV	σ ₀ , mbarn	β	γ
D(γ, n)p	2.23		14.3	1.19	2.55
T(γ, n)D	6.257		9.86	1.7	3.6
T(γ, 2n)p	8.482		22.1	2.11	4.65
³ He(γ, p)D	5.493		21.4	2.43	4.75
³ He(γ, n)2p	7.72		9.48	1.87	3.43
⁴ He(γ, p)T	19.81	$E_γ < 40$	145.5	2.3	7.4
		$E_γ > 40$	19.5	1.0	4.5
⁴ He(γ, n) ³ He	20.57	$E_γ < 50$	60.2	1.8	6.1
		$E_γ > 50$	9.11	0.6	3.5
⁴ He(γ, D)D	25.0	$E_γ < 50$	0.64	1.95	10.0
		$E_γ > 50$	0.01	0.1	4.3
⁴ He(γ, pn)D	28.0		2.1	1.5	3.6
⁴ He(γ, 2p2n)	28.0		0.81	1.1	3.5

^a The fitting formulas give an accuracy of at least 10%.

Note. The spontaneous decay rate of tritium T(β⁻)³He is $k = 1.82709 \pm 0.0026 \times 10^{-9} \text{ s}^{-1}$, see Akulov and Mamyrin (2004).

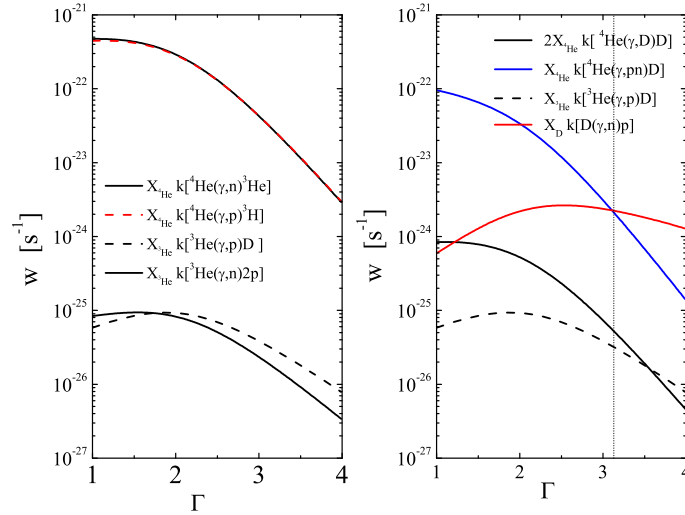


Figure 3. Effective D, ³He and ⁴He production and destruction rates when primordial matter is exposed to γ-rays with energy E = 1–1000 MeV with the spectrum $dN/dE = N_0(E_0/E)^\Gamma$ versus Γ. N_0 corresponds to the γ-ray flux with $L_\gamma = 10^{47} \text{ erg s}^{-1}$ at the distance of 1 kpc.

where the dependence on β, γ and Γ is determined by an integral that can be expressed in terms of Eulers incomplete beta functions:

$$\int_1^{1000/Q} \frac{(x-1)^\beta}{x^{\gamma+\Gamma}} dx = B_1(\Gamma + \gamma - \beta - 1, \beta + 1) + B_{Q/1000}(\Gamma + \gamma - \beta - 1, \beta + 1). \quad (9)$$

The system of equations (4)–(7) is solved analytically. In view of the fitting formulas (8) and (9), the element abundances at any instant of time are expressed in algebraic form in terms of special functions. This allows the distributions of elemental abundances in the medium to be rapidly calculated for various spectral param-

eters. The results of our calculations are presented in Figures 4–12.

The change of the element abundances for a fixed spectral slope Γ is determined by only one parameter $x = F_0 \varepsilon_0^\Gamma t$, the multiplication of the gamma-ray flux at an energy of 1 MeV by the exposure time. We assume that the gamma-ray flux is produced by the central source and is determined only by the distance to the quasar and its luminosity. Taking into account the correlation between the optical and gamma-ray luminosities (Arshakian 2011), we may consider the optical Eddington luminosity $L_{Edd} = 4\pi GMm_p c/\sigma_T = 1.5 \times 10^{46} \text{ M}_8 \text{ erg s}^{-1}$, where σ_T is the Thomson cross section, as an upper limit for the gamma-ray luminosity of sources. The range of admissible cloud exposure times

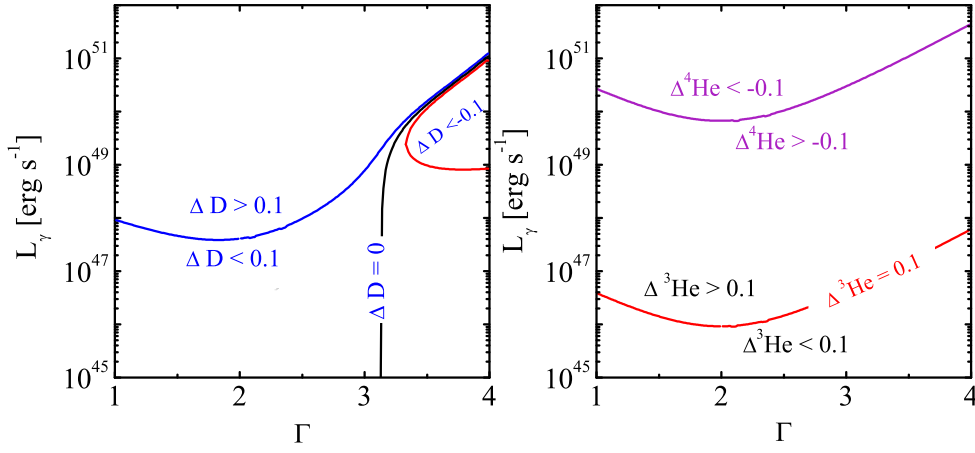


Figure 4. Total luminosity of the γ -ray source L_γ in the energy range 1-10³ MeV versus spectral slope Γ corresponding to a $\pm 10\%$ change in the abundance of D and ³He in the primordial matter at a distance of 1 kpc in an exposure time of 10⁹ yr.

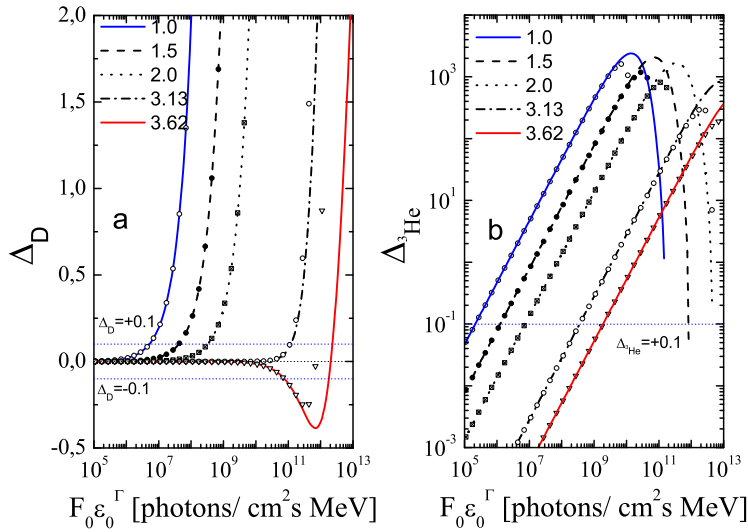


Figure 5. Change of the D (a) and ³He (b) abundances in a medium exposed for 10⁹ yr versus flux density at an energy of 1 MeV $F_0 \epsilon_0^\Gamma$. As the spectral slope Γ increases, the curve is shifted rightward; at $\Gamma > \Gamma_k = 3.13$, the Δ_D curve acquires a negative value (D is destroyed). $\Gamma = 3.62$ corresponds to the minimum flux density $F_0 \epsilon_0^\Gamma \simeq 8 \times 10^{11}$ phot cm⁻² s⁻¹ MeV⁻¹ at which 10% of D will be destroyed in 10⁹ yr.

is estimated via the lifetime of a quasar at its active phase $t = 10^5 \div 10^9$ yr (Martini and Weinberg 2001). We consider the characteristic exposure time $t_0 = 10^9$ yr to be able to compare our results with the work by Boyd et al. (1989) and to take into account the maximally possible effects when estimating the deuterium production.

For the limiting gamma-ray luminosity $L_\gamma = 10^{47}$ erg s⁻¹ (i.e., the Eddington luminosity of a quasar with a mass of $10^9 M_{sun}$), the element abundances changes by $\simeq 10\%$ at distances of ~ 100 pc. The self-similarity of the model allows the radius of influence of the quasar (on the medium's composition) to be recalculated for such quasars of a different luminosity and for a different exposure time by rescaling:

$$R_1 = R_2 \left(\frac{L_1 t_1}{L_2 t_2} \right)^{(1/2)}. \quad (10)$$

In contrast to previous works, we also investigated the dependence of the reaction rates on the spectral

index. For a quasar with a fixed luminosity $L_\gamma = 10^{47}$ erg s⁻¹ in the energy range 1–1000 MeV, the D and ³He production and destruction rates are plotted against the spectral hardness Γ in Fig. 3. These plots describe the dynamics of the medium's composition on short exposure time scales, when the relationship between the abundances of ⁴He and ³He, D in the medium did not change significantly. The maximum in the reaction rates (at $\Gamma \simeq 2$) is determined by the relationship between the position of the maximum in the reaction cross sections and the power-law shape of the spectrum. For deuterium (Fig. 3b), there is a feature $\Gamma = 3.1$. For harder spectra ($\Gamma \leq 3.1$), deuterium in the medium will be only produced (through the photodisintegration of ⁴He); conversely, for softer spectra ($\Gamma \geq 3.1$), the destruction of deuterium can exceed its production. There are no such features for ³He (see Fig. 3a). It is only produced. The contributions from the ³He production during the ⁴He destruction exceeds the ³He photodisinte-

gration by more than two orders of magnitude. Since there are no ${}^4\text{He}$ sources in the model under consideration, ${}^4\text{He}$ is only destroyed. The amount of tritium is established at a constant level (until the ${}^4\text{He}$ abundance changes significantly) determined by the equilibrium condition $dX_T/dt = 0$:

$$X_T = X_{{}^4\text{He}} \frac{k_{{}^4\text{He} \rightarrow T}}{K_T} = X_{{}^4\text{He}}(0) \frac{k_{{}^4\text{He} \rightarrow T}}{K_T} \exp(-K_{{}^4\text{He}} t), \quad (11)$$

where $K_{{}^4\text{He}}$ and K_T denote the total element destruction rates.

The features in the relationships between the reaction rates determine the pattern of changes in the element abundances. Figure 4 define the regions of spectral parameters (the gamma-ray luminosity of the quasar L_γ for an isotropic source and the spectral index Γ) corresponding to a 10% change of the elemental abundances in a cloud Δ_D and $\Delta_{{}^3\text{He}}$ at a distance of 1 kpc in an exposure time of 1 Gyr. As has been pointed out above, the destruction of D is possible in a certain domain of parameters. In Fig. 5, the change in the abundances of D and ${}^3\text{He}$ is plotted against the spectral flux density $F_0 \varepsilon_0^\Gamma$ at an energy of 1 MeV for various spectral indices Γ . The abundance of D and ${}^3\text{He}$ is determined only by the exposure parameter $x \propto F_0 \cdot t$. Therefore, apart from the spatial change in elemental abundances (the flux density decreases as $F_0 \propto r^{-2}$), these plots illustrate the temporal evolution of the D and ${}^3\text{He}$ abundances in the medium.

Another feature in the distribution of deuterium is that when the medium is irradiated by emission with a soft spectrum, the decrease in the mass fraction of D is subsequently (at high flux densities or on long exposure time scales) replaced by a significant increase. This is because a new D production channel appears from the newly produced ${}^3\text{He}$.

5. THE EFFECTIVE RADIUS OF INFLUENCE. AN ISOTROPIC SOURCE

The effective radius of influence of a quasar as a function of its gamma-ray luminosity and spectral hardness in a time of ~ 1 Gyr can be determined within the spherically symmetric quasar emission model. As has been shown above, the characteristic radius of influence of a quasar with a luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$ in the energy range 1–1000 MeV is ~ 100 pc. The Hubble expansion may be neglected at such distances, and the flux density is then related to the luminosity by the standard relation

$$\frac{L_\gamma}{4\pi R^2} = \int_1^{1000} F_\gamma(E) E dE = F_0 \varepsilon_0^\Gamma I(\Gamma), \quad (12)$$

the latter expression was derived by taking into account Eq. (3), where $I(\Gamma) = \frac{1000^{2-\Gamma}-1}{2-\Gamma}$ and $I(\Gamma) = \ln(1000)$ at $\Gamma = 2.0$.

Figures 6 and 7 show the profiles of the D/H and ${}^3\text{He}/\text{H}$ ratios as a function of the quasar distance. The distribution of elements in the medium changes greatly as the quasar is approached. The main change occurs at ~ 100 pc, where the amount of D and ${}^3\text{He}$ increases by two or three orders of magnitude. At shorter distances,

effective photodisintegration of both ${}^4\text{He}$ and D and ${}^3\text{He}$ takes place. Since there are no ${}^4\text{He}$ sources in the model under consideration, the ${}^4\text{He}$ abundance decreases exponentially with increasing flux density or decreasing quasar distance. Thus, the effect of a change in the D and ${}^3\text{He}$ abundances is strongly local (within ~ 1 kpc of the AGN center).

The changes in the element abundances are also sensitive to the spectral hardness Γ . For different spectra, the elemental abundances in the medium can differ by an order of magnitude at the same exposure time and quasar luminosity. Figures 6 and 7 present several curves corresponding to different spectral slopes. The dependence of the radius of influence on the spectral index Γ is determined by the dependence of the reaction rates (see Fig. 3): D and ${}^3\text{He}$ are produced in large quantities and at great distances at $\Gamma \simeq 1.8$ and 2.0, respectively.

6. MOTION OF THE MEDIUM

The distributions of the abundances of light elements formed through photonuclear reactions (see Figs. 6 and 7) were obtained by assuming the medium to be at rest, when the matter at different distances from the quasar center is not mixed. In reality, the matter in the interstellar medium moves, and the distributions of the elements change.

Estimating the global effect of the contribution from the emission of quasars to the change of the D and ${}^3\text{He}$ abundances in the Universe as a whole (after the completion of Big Bang nucleosynthesis), we perform a uniform averaging of the changed D and ${}^3\text{He}$ abundances over the space in which the change occurred:

$$\langle X \rangle (R, L_\gamma, \Gamma) = \frac{\bar{n}}{n_{pr}} = \frac{1}{V} \frac{\int_0^R X(r) 4\pi r^2 dr}{X_{pr}}, \quad (13)$$

where X denotes the abundances of the elements: (D/H), (${}^3\text{He}/\text{H}$) and (${}^4\text{He}/\text{H}$).

The upper limit of the integral R in Eq. (13), which we call the effective zone of influence of a quasar, is chosen from the conditions under which the quasar influence will change the composition of the medium by 10% at 1 Gyr. The limiting quasar luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$ and exposure time $t = 10^9 \text{ yr}$ are used to estimate the maximum influence of the quasar emission on the composition of the medium. The size of the region of influence is ~ 1 kpc for D and ~ 10 kpc for ${}^3\text{He}$. The deviation of the averaged abundance of D and ${}^3\text{He}$ from its primordial value does not exceed 5%; the produced D and ${}^3\text{He}$ are plotted against the quasar distance for various spectral slopes in Figs. 8 and 9. The element abundance averaged over a larger volume decreases in inverse proportion to the distance squared, $\langle X \rangle \propto R^{-2}$.

Thus, the global effect of the gamma-ray emission from quasars (at a limiting isotropic luminosity of $10^{47} \text{ erg s}^{-1}$) on the composition of the medium turns out to be insignificant, and the emission from quasars cannot be considered to be a source of the observed excesses of the D and ${}^3\text{He}$ mass fractions above the primordial values.

However, this estimate obtained by assuming uniform mixing is only a lower limit for the influence of a quasar on the change in the isotopic composition of the

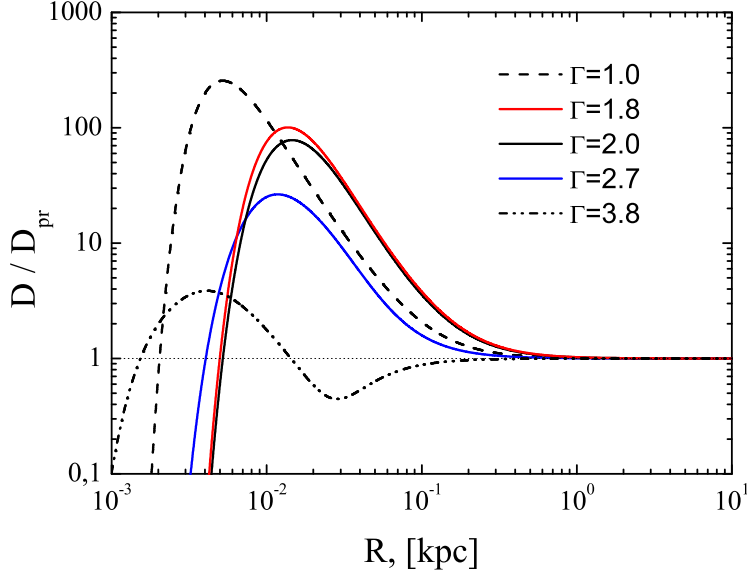


Figure 6. D/H ratios in the medium versus distance to a quasar of luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$. The D abundance relative to its primordial value $(D/H)_{pr} = 2.68 \times 10^{-5}$ is along the vertical axis. The curves are presented for various spectral slopes $\Gamma = 1.0, 1.5, 1.8, 2.7, 3.8$ of a source with the same luminosity. $\Gamma = 2.7$ corresponds to the spectral slope for the quasar emission considered by Boyd et al. (1989). The largest amount of D is produced at $\Gamma = 1.83$.

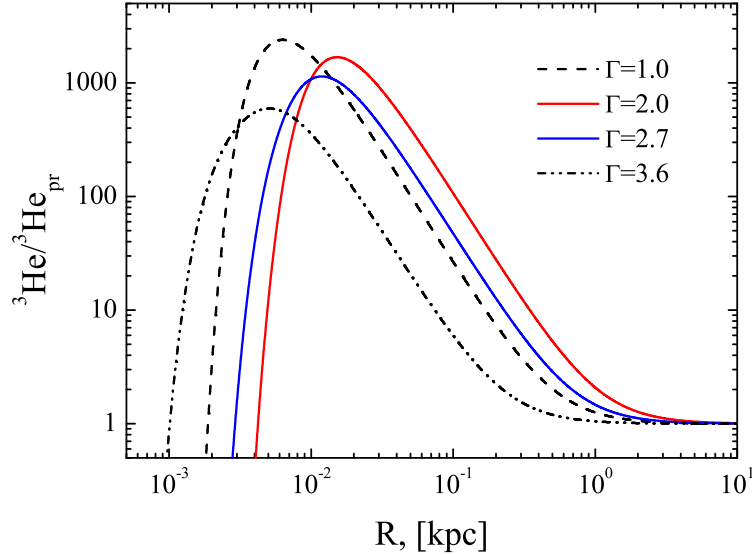


Figure 7. $^3\text{He}/\text{H}$ ratio in the medium versus distance to a quasar of luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$. The ^3He abundance relative to its primordial value $(^3\text{He}/\text{H})_{pr} = 1.06 \times 10^{-5}$ is along the vertical axis. The curves are presented for various spectral slopes $\Gamma = 1.0, 2.0, 2.7, 3.6$ of a source with the same luminosity. $\Gamma = 2.7$ corresponds to the spectral slope of the quasar emission considered by Boyd et al. (1989). $\Gamma = 2.0$, the maximum amount of ^3He is produced in the medium.

surrounding medium. Considering the model of nonuniform mixing, a situation is possible where a cloud of gas overrich in D and ^3He can be accelerated by a jet and be ejected into the medium surrounding the quasar. The matter from the interstellar medium can also fall to the quasar through an accretion disk, be exposed, and then ejected back. The existence of such a mechanism was previously pointed out by Casse et al. (1999).

The pollution of the medium through this mechanism depends on many parameters, such as the relationship between the required matter exposure time near the

quasar and the cloud lifetime near the galactic nucleus, the degree of destruction of the produced elements during the ejection of matter into the intergalactic medium, and the condensation of the ejected matter into small intergalactic clouds. This mechanism seems possible, but a detailed study of the theory of accretion disks around AGNs, the theory of jets, and other theories is needed for its assessment.

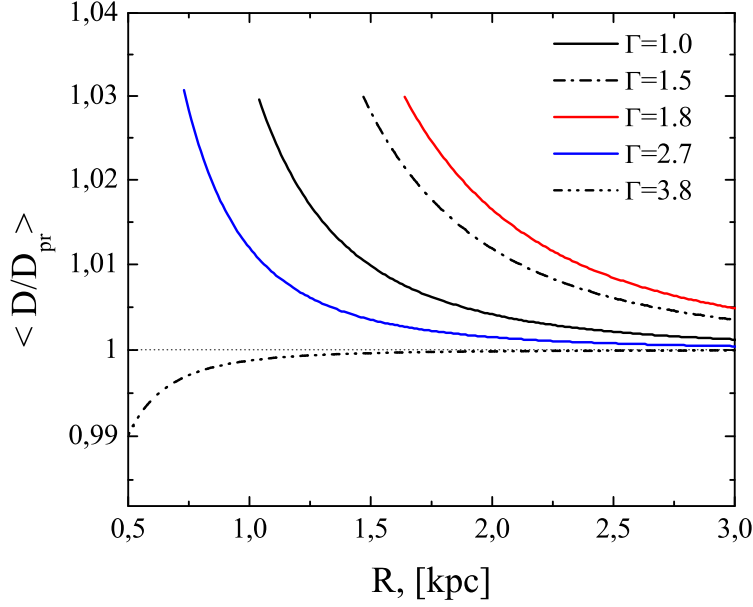


Figure 8. Average D/H ratio versus size of the averaging region corresponding to a change in the composition of primordial matter when exposed to γ -rays with an energy of 11000 MeV from a source of luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$. D/H in units of its primordial value $(D/H)_{pr}$ is along the vertical axis. The curves are presented for several spectral slopes $\Gamma=1.0, 1.5, 1.83, 2.7, 3.8$. $\Gamma = 1.83$ corresponds to the maximum amount of D produced in the medium. Boyd et al. (1989) used the model of a source with a spectral slope $\Gamma = 2.7$.

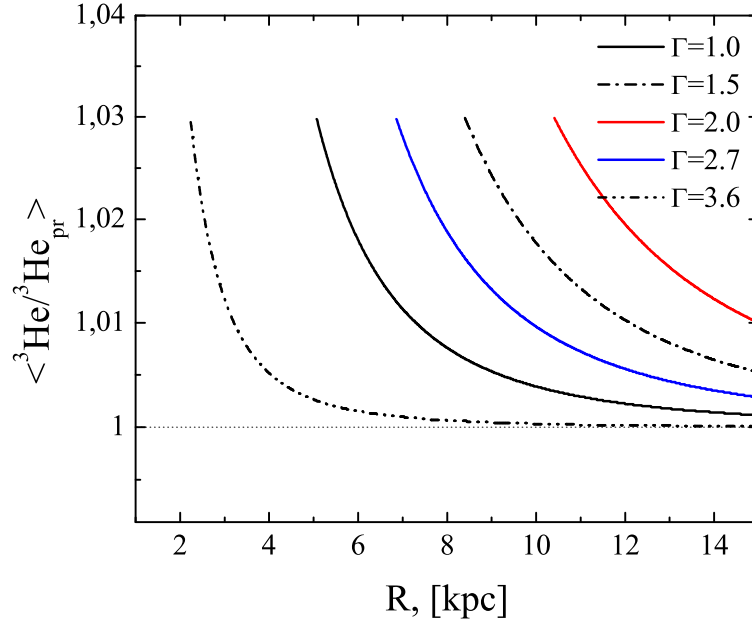


Figure 9. Average $({}^3\text{He}/\text{H})$ ratio versus size of the averaging region corresponding to a change in the composition of primordial matter when exposed to γ -rays with an energy of 11000 MeV from a source of luminosity $L_\gamma = 10^{47} \text{ erg s}^{-1}$. ${}^3\text{He}/\text{H}$ in units of its primordial value $({}^3\text{He}/\text{H})_{pr}$ is along the vertical axis. The curves are presented for several spectral slopes $\Gamma = 1.0, 1.5, 2.0, 2.7, 3.6$. $\Gamma = 2.0$ corresponds to the maximum amount of ${}^3\text{He}$ produced in the medium. Boyd et al. (1989) used the model of a source with a spectral slope $\Gamma = 2.7$.

7. DISCUSSION

Previously, the influence of photodisintegration processes on the abundances of light elements was considered by Boyd et al. (1989) using the galactic center of NGC 4151 as an example for the chosen spectral slope $\Gamma = 2.7$. The gamma-ray flux with $E > 2 \text{ MeV}$ was assumed to be $F = 4 \times 10^{16} \text{ phot cm}^{-2} \text{ s}^{-1}$ at

a distance of 2 lt-days (the corresponding luminosity is $L_\gamma \simeq 1.6 \times 10^{44} \text{ erg s}^{-1}$ in the energy range 1–1000 MeV). On the whole, our calculations reproduce the results of this paper, but there are also differences (see Fig. 10). In particular, to estimate the reaction rates, the authors used reaction cross sections (normalized to the gamma-ray flux) that turned out to be

slightly overestimated. Table 3 compares the data from Boyd et al. (1989) with the values obtained by our fitting of the new data. The difference between the cross sections for some reactions reaches 200%.

Using the same reaction cross sections and initial element mass fractions as those taken by Boyd et al. (1989), we reproduced the results of this paper. However, in the region $r < 10$ lt-years, where the authors disregarded the change in the abundance of ^4He , the results disagree. According to our calculations, as the galactic center is approached, the amount of D and ^3He does not reach a constant level but reaches its maximum value at $r \sim 4 - 7$ light years. Subsequently, as the galactic center is approached, the element abundances will not remain constant, because the photodisintegration of all elements begins to dominate as the flux increases. Accordingly, the change in the abundance of ^4He should be taken into account to correctly estimate the influence of gamma-ray emission on the isotopic composition of the medium in the immediate neighborhood of the AGN.

The depletion of ^4He was taken into account by Balbes et al. (1996), who also considered the influence of photonuclear reactions on the primordial composition of the medium in the Universe. Figure 12 compares the results of our calculations with those from Balbes et al. (1996). Our calculations reproduce the results of this paper. Nevertheless, these authors did not consider the dependence of the D and ^3He production on the spectral parameters of the emission L_γ and Γ by assuming that the cross sections for spectra of different hardness increased by no more than a factor of 4, which actually is not the case. When varying the spectral hardness, the reaction cross sections change by one or two orders of magnitude.

In contrast to Boyd et al. (1989) and Balbes et al. (1996), we considered the influence of spectral hardness Γ on the produced amount of D and ^3He . We found that the amount of D and ^3He produced in the zone of influence of a quasar for spectra of different values of the spectral index could exceed the value found by Boyd et al. (1989) by a factor of 7 for D and a factor of 3 for ^3He . We retained the quasar luminosity $L_\gamma = 1.6 \times 10^{44} \text{ erg s}^{-1}$, changing only the distribution of gamma-ray photons over the spectrum (various spectral indices). The derived dependencies are shown in Fig. 11. Thus, the effect studied by Boyd et al. (1989) using the galactic center of NGC 4151 as an example may turn out to be negligible if soft spectra with $\Gamma \geq 3$ are considered or be more significant for harder spectra with $\Gamma \simeq 2$ relative to $\Gamma = 2.7$ used by Boyd et al. (1989).

New observations of quasars and blazars (see, e.g., Arshakian 2011) give an upper limit on the blazar luminosity in the energy range 1–1000 MeV of $10^{49} \text{ erg s}^{-1}$. This increases the effective zone of influence by more than three orders of magnitude (provided that the activity time of the nucleus is the same). Note, however, that the emission for blazars is localized in a narrow region corresponding to the jet and only in this region is a high value of the characteristic distance of the influence of emission on the medium possible. According to our calculations, it is ~ 1 kpc for D and ~ 10 kpc for ^3He . In the case where the isotropic source emission

Table 3. Comparison of the reaction cross sections.

Reaction	$\langle \sigma \rangle$, mbarn	
	Boyd et al. (1989)	our calculation
$\text{D}(\gamma, n)p$	1.62	1.33
$^3\text{He}(\gamma, p)\text{D}$	0.103	0.073
$^3\text{He}(\gamma, n)2p$	0.066	0.050
$^4\text{He}(\gamma, p)\text{T}$	0.017	0.015
$^4\text{He}(\gamma, n)^3\text{He}$	0.017	0.015
$^4\text{He}(\gamma, \text{D})\text{D}$	5.5×10^{-5}	2.62×10^{-5}
$^4\text{He}(\gamma, pn)\text{D}$	0.0013	0.00124

model can be applied, the gamma-ray luminosity of a quasar typically does not exceed $10^{47} \text{ erg s}^{-1}$, i.e., the optical Eddington luminosity of a quasar with a mass of $10^9 M_{\text{sun}}$. In this case, the distance at which the D and ^3He abundances change locally are, respectively, ~ 100 pc and 1 kpc for ^3He . The derived radii of influence turned out to be comparable to the characteristic distances at which the structure of the quasar itself (the source being non-point like, the accretion disk, and the jet) should be taken into account. A detailed account of the objects structure can cause the effects to increase. In the process of its accretion onto an active nucleus through an accretion disk, being in the immediate vicinity of the active nucleus, the matter can be irradiated by considerably larger gamma-ray fluxes and, accordingly, can change its isotopic composition in a shorter time. The D- and ^3He -enriched matter ejected into the interstellar and intergalactic medium can cause the isotopic composition of the medium at great distances from the AGN to change.

As an example, the application of the examined mechanism of the change in the isotopic composition of the medium to our Galaxy can be considered for the so-called ‘ ^3He Problem’. Thus, the absence of a $^3\text{He}/\text{H}$ gradient (Bania et al. 2007) in our Galaxy allows a limit to be placed on the activity time of the Galactic nucleus in the past. The hyperfine transition line of $^3\text{He}^+$ (8.665 GHz) observed in HII regions and planetary nebulae is used to determine the amount of ^3He in the interstellar medium. The $^3\text{He}/\text{H}$ ratio is determined via the $^3\text{He}^+/\text{H}^+$ ratio. The ^3He abundance at Galactocentric distances from 0 to 16 kpc turns out to be at the same level, $^3\text{He}/\text{H} = 1.79 \pm 0.65 \times 10^{-5}$. At a smaller Galactocentric distance, ^3He was observed only in the HII region of the source Sgr B2 in 1990 (Balser 1994): $^3\text{He}/\text{H} = 2.49 \times 10^{-5}$, the distance to Sgr B2 was found to be $r = 0.09 \pm 0.03$ kpc (Reid et al. 2009).

Assuming that the increase in $^3\text{He}/\text{H}$ relative to its primordial value $(^3\text{He}/\text{H})_{\text{pr}}$ was caused only by photonuclear reactions, we can estimate the activity time of the Galactic nucleus in the past. The mass of the supermassive black hole at the center of our Galaxy, $M_{\text{BH}} = 4.5 \pm 0.4 \times 10^6 M_{\text{sun}}$ (Ghez et al. 2008), turns out to be so small that to produce the observed amount of ^3He at a distance of 100 pc, the medium should be exposed at the Eddington luminosity limit of the Galactic nucleus $L_{\text{Edd}} = 6.75 \times 10^{44} \text{ erg s}^{-1}$ for $t_0 \leq$

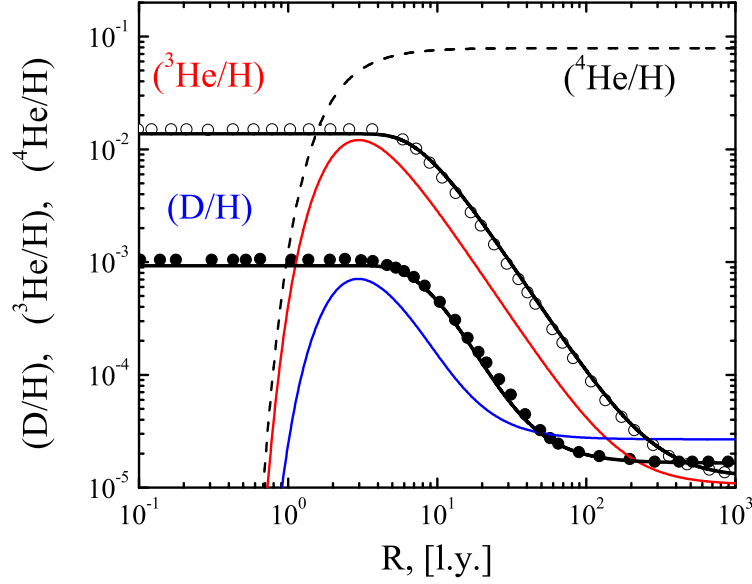


Figure 10. $(^4\text{He}/\text{H})$, $(^3\text{He}/\text{H})$ and (D/H) abundances versus distance to the galactic center of NGC 4151. The circles indicate the $^3\text{He}/\text{H}$ and D/H curves from Boyd et al. (1989). The solid curves represent our calculations with the data from Boyd et al. (1989). The dashed curves represent our complete calculations.

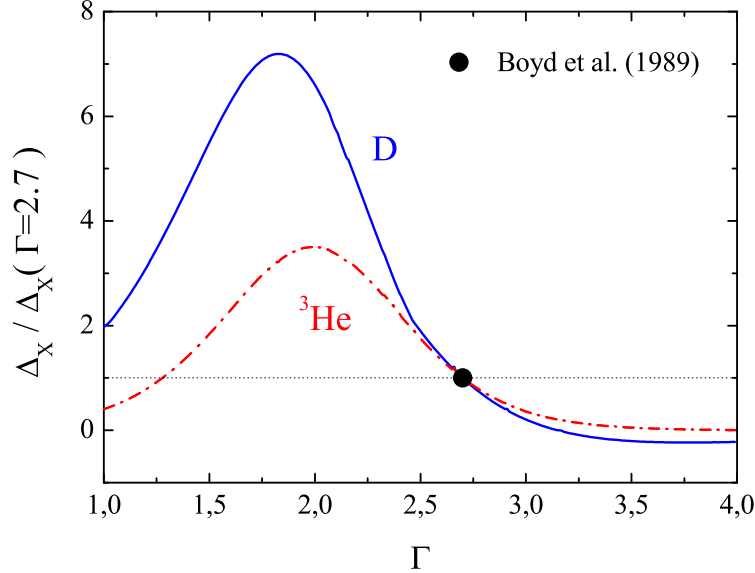


Figure 11. Relative amount of produced D and ^3He through photonuclear reactions in the zone of influence of the galactic center of NGC 4151 for 1 Gyr versus spectral hardness Γ . The values are normalized to the amount of D and ^3He produced when the medium is exposed to emission with a spectrum with $\Gamma = 2.7$ (this value was considered by Boyd et al. (1989)). The maximum amount of D is produced at $\Gamma = 1.83$ and exceeds the value from Boyd et al. (1989) by more than a factor of 7. The maximum amount of ^3He corresponds to $\Gamma = 2.0$.

$1.7 \pm 0.9 \times 10^9$ yr (see Fig. 13), which exceeds considerably any reasonable estimates of the lifetime for the nuclei. Some indirect data on the deuterium abundance point to the existence of a gradient with Galactocentric distance (Lubowich and Pasachoff 2009). This can be due to both deuterium astration in stars and complex chemistry of the interstellar medium.

8. CONCLUSIONS

We considered the influence of photonuclear reactions on the change in the composition of the interstellar

medium. Directional exposure of the medium to gamma-ray emission was shown to cause the relative D and ^3He abundances in the medium to increase.

We calculated the photonuclear reaction rates as a function of the spectral hardness of the emission. We fitted the photodisintegration reaction cross sections by analytical formulas using which the reaction rates can also be expressed analytically in terms of Eulers beta functions.

In comparison with previous works (Boyd et al. 1989; Balbes et al. 1996; and others, $L = 10^{44} \text{ erg s}^{-1}$, $\Gamma = 2.7$), we considered power-law spectra with various values of

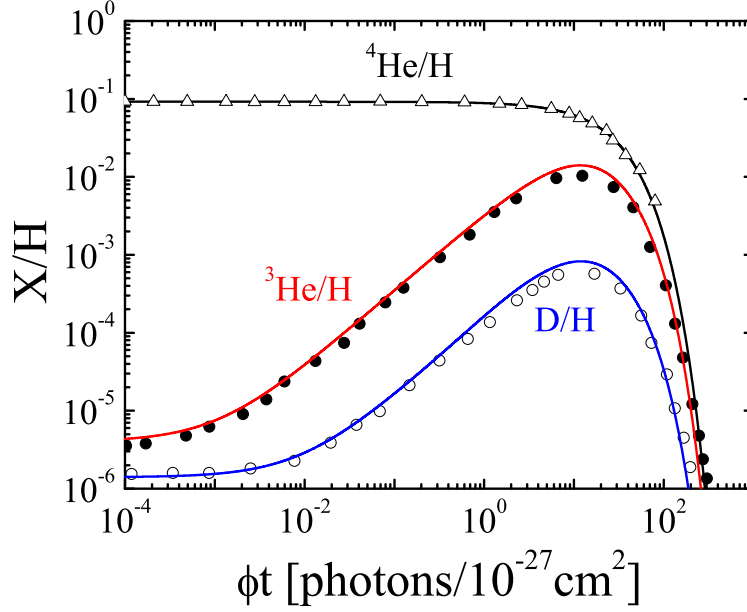


Figure 12. ($^4\text{He}/\text{H}$), ($^3\text{He}/\text{H}$) and (D/H) abundances versus exposure parameter $x = L_\gamma t / 4\pi r^2$. The dots indicate the $^4\text{He}/\text{H}$, $^3\text{He}/\text{H}$, and D/H curves from Balbes et al. (1996) for $\eta_{10} = 100$ (Fig. 1). The solid curves represent our calculations.

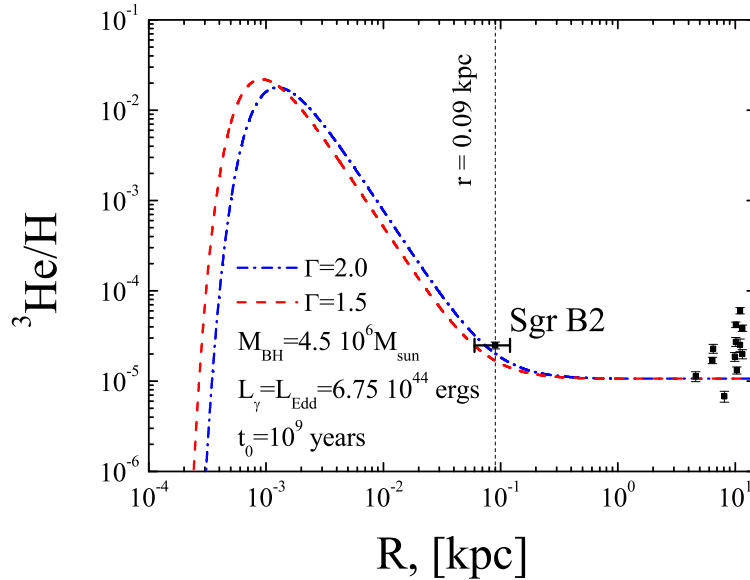


Figure 13. The dots indicate the experimental data on the ^3He abundance in the Galaxy as a function of the Galactocentric distance. The nearest measurement was made in the HII region of Sgr B2. The dashed curve indicates the theoretical calculation of the ^3He abundance in a region exposed to gamma-ray emission from the galactic center at the Eddington luminosity limit for 10^9 yr. The ^3He abundance curve for spectra of different hardness is within the measurement accuracy of the distance to Sgr B2.

$\Gamma = 1 \div 4$ and took into account the high gamma-ray luminosities of quasars, $L \simeq 10^{47} \text{ erg s}^{-1}$. Allowance for the spectral hardness in the model under consideration leads to a change in the final mass fractions of the elements by a factor of 37.

The global effect from the production of D and ^3He through the quasar emission in the Universe, on the whole, turns out to be insignificant. However, this is not the case if the changes in the composition of the medium are considered in a local region. The ejected matter with a changed isotopic composition can condense into clouds

of interstellar and intergalactic gas, thereby changing the composition of such clouds. A further development of the model requires a detailed analysis of the structure of AGNs, i.e., allowance for the extent of the jets, the finite sizes of the accretion disk, and the possibility of the matter processed in the disk being ejected into the interstellar medium, which can cause the isotopic composition of the medium at great distances to change.

Within the model under consideration, the absence of a $^3\text{He}/\text{H}$ gradient in the Galaxy constrains the activ-

ity time of the Galactic center at its Eddington luminosity limit ($L = 6.75 \times 10^{44} \text{ erg s}^{-1}$) $t_0 \leq 1.7 \pm 0.9 \times 10^9 \text{ yr}$.

9. ACKNOWLEDGMENTS

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